X-ray and fusion yields at the impact of atomic clusters on targets

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Abstract: Theoretical curves are given for the power and spectral intensity of the bremsstrahlung radiation generated by the collision of deuterium-tritium clusters, as a function of their radius, mean energy per particle and concentration of particles in the cluster, for different values of the gain parameter G and of the compression parameter F. In order to estimate the importance of the radiative processes, the energy radiated during the time of inertial confinement is compared with the initial energy of the region of impact. We also investigate the spectral distribution of the radiation emitted in the region of impact, both in the low-energy region and for photon energies which are comparable or larger than the plasma temperature T. Then we study the fusion gain for the collision of two clusters, for DT, DD, D^3He, p^6Li and $p^{11}B$ fusion processes, assuming that the particle concentration is that corresponding to the normal, uncompressed state of the clusters. The gain G is calculated as a function of T for several values of the cluster radius. Moreover, the radius of the clusters for which the gain has the value G=1 is represented as a function of the plasma temperature T, and we determine the incident energy required in the center-of-mass system to obtain a gain G=1 at a temperature T by cluster impact, for the afore-mentioned fusion processes. The requirement on the incident energy for a gain G=1 by uncompressed cluster impact is of about 1 MJ for the DT reaction, and is very much larger for the other fusion processes.

1. Emission of X radiation at the impact of atomic clusters on a target

In this work, theoretical curves are given for the power and spectral intensity of the bremsstrahlung radiation generated at the impact of deuterium-tritium clusters, [1] as a function of their radius, mean energy per particle and concentration of particles in the cluster. We studied the center-of-mass collision of two equimolar deuterium-tritium clusters of radius r, concentration n, and incident velocity v, and we have assumed that as a result of the impact of the two clusters a region of hot plasma is created of temperature T, expressed in keV, the radius of the region being $2^{1/3}$ r. The bremsstrahlung energy radiated per unit volume, time and solid angle, for one polarization direction, is $j=n^2 (2\pi/3)^{1/2} (2\pi e^6/96\pi^4\varepsilon_0^3 hmc^2) (T/mc^2)^{1/2} G_1$, where the factor G_1 can be obtained by numerical analysis, has values of the order of unity, and for large values of the energy of the electrons converges to the value $2 \times 3^{1/2}/\pi$. [2] The power radiated per unit volume is $P=5.35 \times 10^{-31} n^2 T^{1/2}$, where P is expressed in W/cm^3, n in $nuclei/cm^3$, and T in keV. The total power emitted in the region of impact is then $P_{tot}=(8\pi r^3/3) P$. We have assumed that the radius r and the concentration n are related as

$$(1/2)n\langle\sigma v\rangle(r/v_T)=G(3T/E_{DT}) , \qquad (1)$$

where $v_T=(3kT/m_{DT})^{1/2}$, σ is the cross section of the DT fusion reactions, $m_{DT}=4.17 \times 10^{-27}$ kg is the average of the D and T masses, and E_{DT} =17.6 MeV is the energy released in a fusion process, so that the quantity G has the significance of a gain parameter for the process.

In Fig. 1 the power P_{tot} is represented as a function of the temperature of the region of impact for the case when relation (1) is fulfilled, for particle densities in the clusters expressed as n/n_s =F, where n_s is the density of equimolar deuterium-tritium, n_s =4.5 x 10^{22} nuclei/cm^3 . The quantity P_{tot} is proportional to G^3/F, and has been represented for several values of this parameter. In order to estimate the importance of the radiative processes we have compared the energy radiated during the time r/v_T , which is given by $E_{rad} = P_{tot}\, r/v_T$, where v_T is the average thermal velocity of the nuclei, with the initial energy of the region of impact, given by $E_{in} = (8\pi\, r^3/3)n(3kT)$. The ratio of these two quantities is represented in Fig. 2, for the cases G=1 and G=10. The spectral distribution of the radiation emitted in the region of impact is described in the low-frequency region by the function $G_2 = (3^{1/2}/\pi)\ \ln\,(8\pi T/\gamma h\omega)$, where $\gamma = e^C$, C=0.577 being the constant of Euler, and $E_{ph} = h\omega/2\pi$ is the photon energy. This region of frequencies is represented in Fig. 3 by the dotted line. For photon energies which are comparable or larger than the temperature T, the spectral distribution is given by $G_2 = (3^{1/2}/\pi)\ e^{-h\omega/4\pi T}\ K_0(h\omega/4\pi T)$, where K_0 is the modified Bessel function of order 0. This region of the distribution is represented in Fig. 3 by the continuous line. The radius of the incident clusters is given according to Eq. (1) by $r = (6GT/Fn_s\, E_{DT})\ (v_T/\langle\sigma v\rangle)$. The radius r is represented in Fig. 4 as a function of the temperature T, for several values of the parameter G/F. The total initial energies E_{in} for the radii calculated in this way are shown in Fig. 5, for several values of the parameter G^3/F^2. So far we have assumed that the radius of the clusters and their concentration are related according to Eq. (1). However, the energy radiated at the impact of a cluster in a cavity could in principle be used for the compression of a separate fusion target. We have represented in Fig. 6 the power P_{tot} emitted from the region of impact as a function of the initial energy E_{in} put in the impact region, as a function of temperature.

The values obtained in this analysis show that the bremsstrahlung radiation has a significant contribution to the energy balance of the processes in the region of impact, which is due to the quadratic dependence of these processes with the particle density, the latter having relatively large values for inertial fusion. At the same time, Fig. 2 shows that in the region of higher temperatures, the radiation emitted by bremsstrahlung represents only a small fraction of the total energy involved in the fusion process. This leaves open the possibility toward an ignition scheme based on the conversion of incident kinetic energy into thermal energy. The large rates for the bremsstrahlung emission, represented in Fig. 6, suggest also the possibility of using incident clusters for the generating of X radiation inside a cavity, to be used for the compression of fuel capsule by the indirect approach.

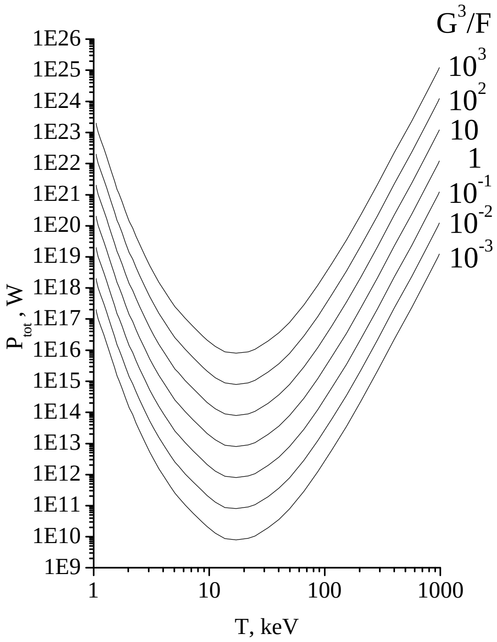

FIG. 1. Total radiated power

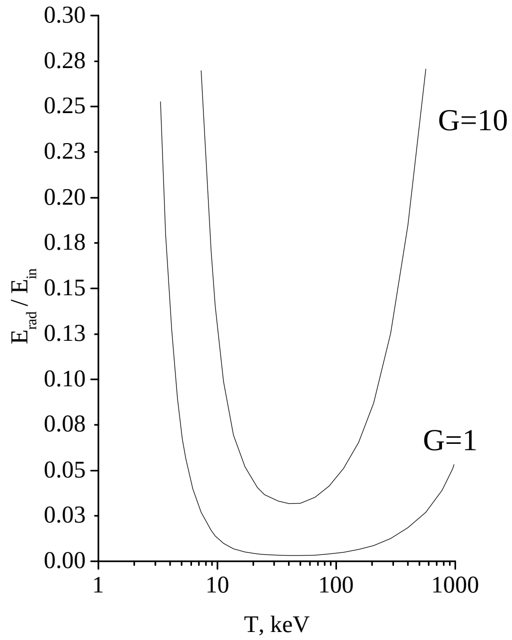

FIG. 2. Ratio of radiated to initial energy

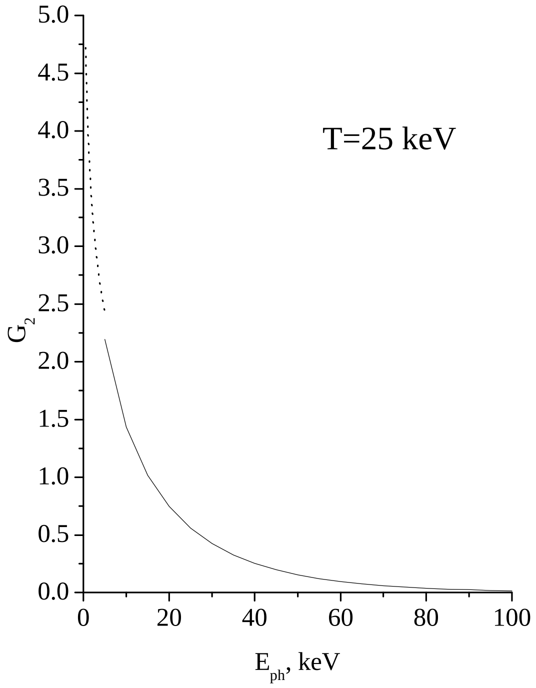

FIG. 3. Relative spectral intensity for a temperature T=25 keV

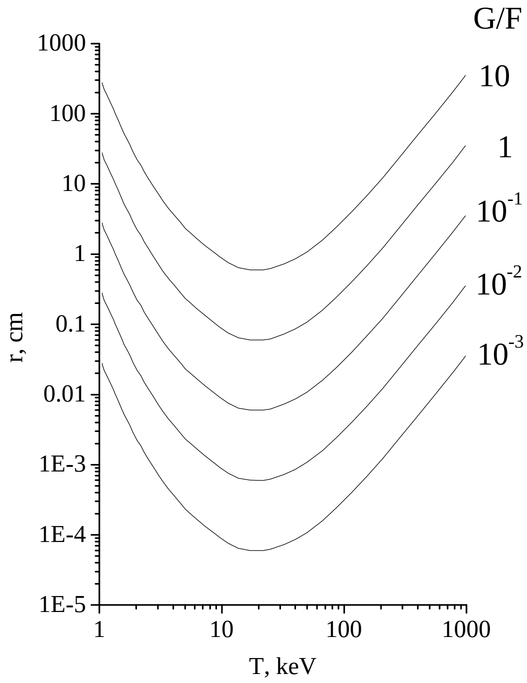

FIG. 4. Radius of incident cluster as a function of energy

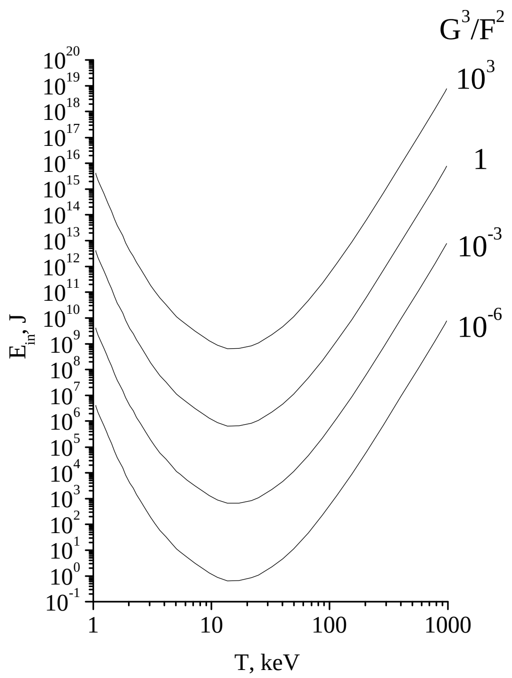

FIG. 5. Initial energy as a function of temperature

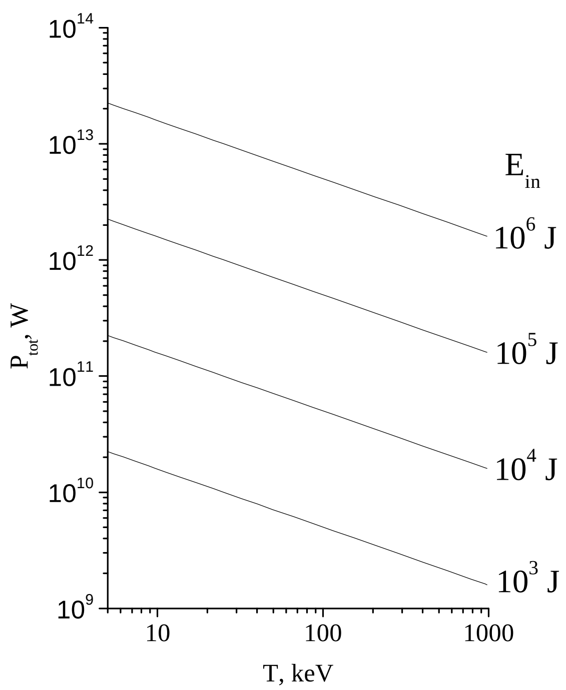

FIG. 6. Radiated power for various initial energies

2. Fusion yield for atomic clusters incident on a fusion target

We studied the fusion gain for the center-of-mass collision of two clusters of radius r, particle concentration n and incident velocity v. We have assumed, as previously, that as a result of the impact of the two clusters a region of hot plasma is created of temperature T, expressed in keV, the radius of the region being $2^{1/3}$ r. The gain has been evaluated as

$$G=n\langle\sigma v\rangle(r/v_T)\,(E_Q/3T)\,[1+(Z_1+Z_2)/2]^{-1}, \qquad (2)$$

where Z_1 and Z_2 are the charges of the reacting nuclei, and E_Q is the energy released in a fusion process. In this section it will be assumed that the particle concentration n is that corresponding to the normal, uncompressed state of the incident clusters. The use of compressed targets improves the gain and decreases the energy requirements in the incident state, but since on the other hand the correlation between the collision dynamics and the compression process is difficult to achieve, we have restricted ourselves to the study of fusion processes with uncompressed clusters.

The gain G has been represented in Fig. 7 for DT processes as a function of the plasma temperature T for several values of the radius r, using n=4.5 x 10^{22} particles/cm^3, E_Q=17.6 MeV. Due to the relatively large values of $\langle\sigma v\rangle$ for the DT fusion processes, it can be seen from Fig. 7 that a gain G=1 could be achieved for incident clusters having a radius of the order of r=1 mm, for a plasma temperature of the order of 20 keV. In this model, the gain decreases linearly with the radius r. The gain parameter G has also been calculated in Fig. 8 for $p^{11}B$ fusion processes, for n=3.34 x 10^{23} nuclei/cm^3, which corresponds to B_9H_{15}, and Q_E=8.68 MeV. As can be seen from Fig. 8, the $p^{11}B$ fusion process remains in principle interesting, although the maximum gain for the $p^{11}B$ process occurs for a plasma temperature around 200 keV. In Fig. 9 we have represented the radius of the clusters for which the gain is G=1 as a function of the plasma temperature T, for the various fusion processes discussed previously. It can be seen from Fig. 9 that the most suitable process for the production of

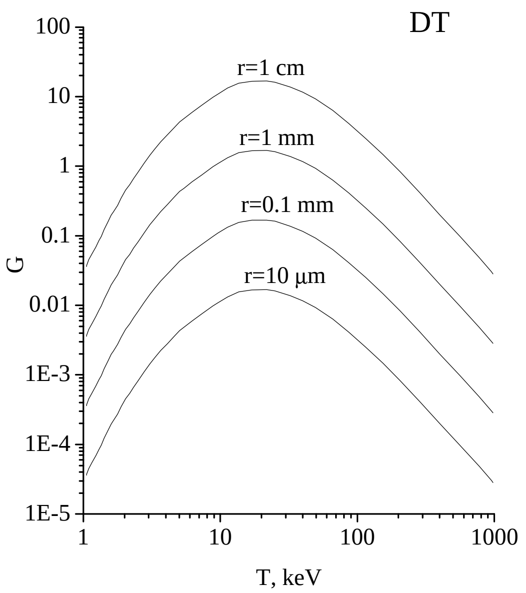

FIG. 7. Gain for DT fusion processes as a function of temperature

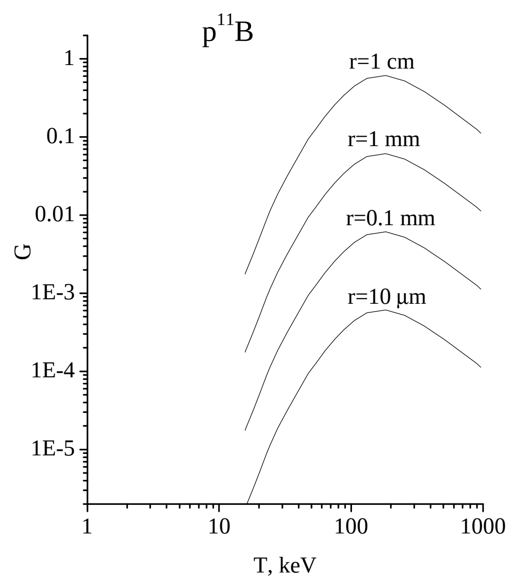

FIG. 8. Gain for $p^{11}B$ fusion processes as a function of temperature

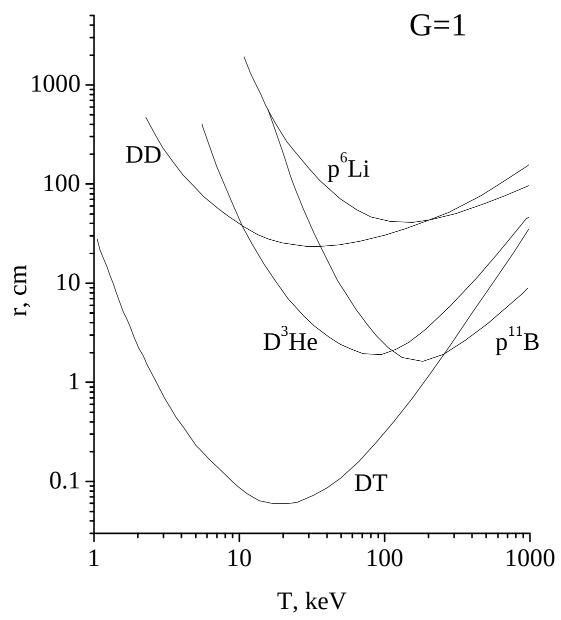

FIG. 9. Radius of incident clusters for a gain G=1 as a function of temperature

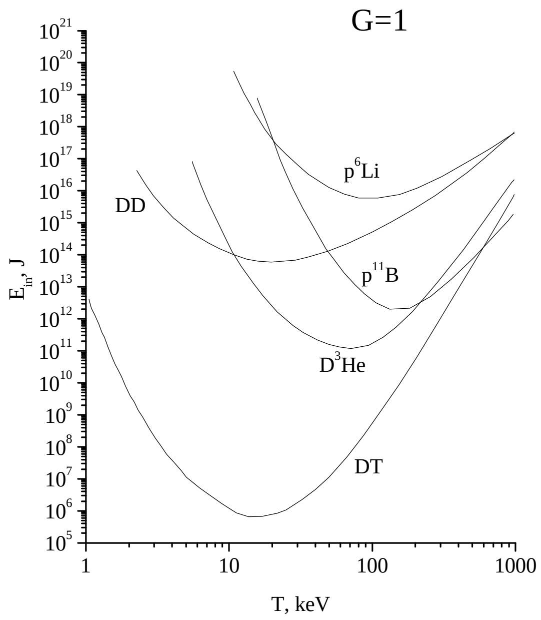

FIG. 10. Incident energy required to produce a gain G=1

fusion reactions by cluster impact remains the DT reaction, both as regards the dimensions of the incident clusters and as regards the incident energy per nucleon, with the D^3He and the $p^{11}B$ reactions sensibly far behind, but still interesting. In Fig. 10 we show the incident energy required in the center-of-mass system to obtain a gain G=1 at a plasma temperature T by cluster impact. The requirement on the incident energy for G=1 by uncompressed cluster impact is of about 1 MJ for DT reactions, and is much larger for the other fusion processes.

References

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[2] ECKER, G., "Theory of Fully Ionized Plasmas, Academic Press, New York (1972).